DEVELOPMENT OF EVALUATION SYSTEM FOR GROUNDWATER LEVEL IN RELATION TO SLOPE STABILITY FORECASTING

NG SOON MIN

UNIVERSITI SAINS MALAYSIA

2016

DEVELOPMENT OF EVALUATION SYSTEM FOR GROUNDWATER LEVEL IN RELATION TO SLOPE STABILITY FORECASTING

by

NG SOON MIN

Thesis submitted in fulfillment of the requirements
for the degree of
Doctor of Philosophy

April 2016

PEMBANGUNAN SISTEM PENILAIAN PARAS AIR BUMI BAGI RAMALAN KESTABILAN CERUN

oleh

NG SOON MIN

Tesis yang diserahkan untuk memenuhi keperluan
bagi ijazah
Doktor Falsafah

April 2016

ACKNOWLEDGEMENT

I would like to take this opportunity to express my utmost gratitude to all who gave me the possibility to complete this thesis successfully. First of all, I want to thank my main supervisor, Dr Mohd Ashraf Mohamad Ismail for his excellent guidance and advices throughout the completion of my PhD research. His valuable encouragement, time spent and patience dedicated to my study are greatly appreciated.

I would also like to thank my co-supervisor Professor Dr. Ismail bin Abustan who has given me a lot of invaluable comments and constructive suggestions to conduct this research successfully.

Special gratitude to Mr Ahmad Halmi, Mr Zabidi, Mr Dziauddin, Dr Tan Chee Ghuan, Mr Rais, Mr Firdaus and also all the staffs in school of Civil Engineering for their assistance in the laboratory, field and administrative works. My special thanks also go to my fellow peers for their moral support and interesting discourse sessions during my studies.

Aside from this, I would like to acknowledge Universiti Sains Malaysia for the Postgraduate Research Grant Scheme (USMRU-PRGS) (1001/PAWAM/8046010) and USM Research University Grant (1001/PAWAM/814192) that provide me the financial assistance to carry out this study smoothly.

To my family, I owe them a special debt for giving me such a huge encouragement and support throughout my studies. Finally, my deepest appreciation is also dedicated to my beloved soul mate Catherine Van for her continuous motivation and companionship to complete this thesis successfully.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

1D	One dimensional
2D	Two dimensional
3D	Three dimensional
AEV	Air entry value
BSCS	British Soil Classification System
CU	Consolidated undrained triaxial test
EDM	Electronic distance meter
FEM	Finite element method
FEM-SSR	Finite element shear strength reduction method
FOS	Factor of safety
GLE	General limit equilibrium
GP	Genetic programming
GPS	Global positioning system
GWT	Groundwater table
HAE	High air entry
ID	Intensity-duration
IDW	Inverse distance weighting
LEM	Limit equilibrium method
LP	Local polynomial
lpm	Litre per minute
MG	Gravelly silt
MH	High plasticity silt
MI	Intermediate plasticity silt

MS	Sandy silt
NN	Nearest neighbour
NSMP	National Slope Master Plan of Malaysia
PTFE	Polytetrafluoroethylene
RMS	Root mean square
RQD	Rock quality designation
SP	Poorly graded sand
SPT	Standard penetration test
SSR	Shear strength reduction
SWCC	Soil Water Characteristic Curve
TCR	Total recovery ratio
TDR	Time domain reflectometry
TSA	Trend surface analysis
VBA	Visual basic for application

LIST OF SYMBOLS

σ’	Effective normal stress
σ	Total normal stress
u_a	Pore air pressure
ψ	Matric suction
u_w	Pore water pressure
θ	Volumetric water content
θ_s	Saturated volumetric water content
a	Air entry value
n	Parameter that controls the slope of SWCC function
m	Parameter related to residual water content
C_r	Correction factor
k_w	coefficient of hydraulic conductivity
k_s	saturated coefficient of hydraulic conductivity
Θ	θ/θ_s
p	fitting parameter corresponding to the slope of hydraulic conductivity function
e	natural number of 2.71828
$C(\psi)$	Correction factor
θ_r	Residual water content
b	ln(1000000)
y	dummy variable of integration representing the logarithm of integration
h	total hydraulic head
k_x	Coefficient of hydraulic conductivity in *x*-direction
k_y	Coefficient of hydraulic conductivity in *y*-direction

Q	Applied boundary flux such as evaporation, infiltration etc.
m_w	Slope of the SWCC
τ	Shear stress on the failure plane
c'	Effective cohesion
ϕ'	Effective angle of internal friction
ϕ^b	Angle indicating the rate of increase in shear strength relative to the change in matric suction, $(u_a-u_w)_f$
c_f	Factored cohesion
ϕ_f	Factored angle of internal friction
$\mathrm{v_p}$	P-waves velocity
I	Rainfall intensity
D	Rainfall duration
R_c	Computed data for inverse distance weighting method
R_i	Measured data at site
N	Total points measured
w_i	Weighting for each point
d_i	Distance from each points measured to the unknown points
α	Exponent
R	Coefficient correlation
c	Total cohesion
ϕ	Total angle of internal friction
k_a	Dielectric constant
c_v	Velocity of light in free space (3 x 10^8 m/s)
t	Time
L	Length
α_i	Discharge coefficient in tank model

β_i	Discharge coefficient for infiltration in tank model
H_i	Height of lateral outlet in tank model
Q_i	Lateral flow discharge in tank model
Z_i	Water level in tank model
I_i	Vertical infiltration discharge
E	Evaporation rate
GWT_{ref}	Reference groundwater table
GWT_c	Computed groundwater table
GWT_o	Observed groundwater table
M	Total number of data measurements
ψ_i	Suction pressure corresponding to the water content occurring at the inflection point of the curve
s	Slope of the line tangent to the function that passes through the inflection point
N_s	Slice base normal force
W_s	Slice weight
l_l	Line load
β, R, x, f, d, w	Geometric parameters of a circular slip surface
α	Inclination of slice base
F_m	FOS equations with respect to moment equilibrium
F_f	FOS equations with respect to horizontal force equilibrium

PEMBANGUNAN SISTEM PENILAIAN PARAS AIR BUMI BAGI RAMALAN KESTABILAN CERUN

ABSTRAK

Penyelidikan ini bertumpu kepada pembangunan sistem penilaian paras air bumi bagi ramalan kestabilan cerun berdasarkan kajian kes bertempat di cerun Presint 9, Putrajaya, Malaysia. Sistem ini melibatkan pembangunan model konseptual subpermukaan, pembangunan model untuk penilaian turun naik paras air bumi dan penilaian kestabilan dan penyiasatan perilaku tanah tak tepu yang merangkumi tekanan liang udara. Pencirian subpermukaan untuk kawasan kajian telah dijalankan dengan menggunakan integrasi lubang gerudi, kajian pembiasan seismik dan kaedah keberintangan elektrik. Model subpermukaan tiga dimensi (3D) yang terdiri daripada stratigrafi, halaju seismik dan keberintangan elektrik berjaya mengenal pasti zon kegagalan cerun berpotensi tinggi yang juga merangkumi kawasan kegagalan cerun lampau. Zon kegagalan yang terdiri daripada tanah kelodak dikenal pasti mempunyai ciri-ciri kandungan air yang tinggi dengan julat keberintangan elektrik dari 10Ωm ke 300Ωm dan julat halaju gelombang P (v_p) yang sederhana dari 500m/s ke 1000m/s. Ini diikuti dengan pembangunan model tangki pelbagai dan analisis berangka untuk menentukan perubahan air bumi dan taburan tekanan liang air di dalam cerun. Model tangki pelbagai berjaya menghasilkan ralat punca kuasa dua (RMSE) bernilai 0.156 dan 0.169 untuk model kalibrasi yang menggunakan data tahun 2011 dan model ramalan yang menggunakan data tahun 2012. Faktor keselamatan (FOS) cerun sepanjang tahun 2012 menunjukkan perubahan berdasarkan turun naik paras air bumi yang dianalisis menggunakan kaedah keseimbangan had (LEM) dan kaedah unsur

terhingga (FEM). Disamping itu, FOS untuk model cerun yang menggunakan paras air bumi model tangki pelbagai memperoleh ralat sebanyak 1% berbanding dengan model cerun yang menggunakan paras air bumi ukuran di tapak. Keputusan kajian membuktikan bahawa sistem penilaian yang dibangunkan ini boleh diterapkan sebagai satu sistem penilaian untuk ramalan kestabilan cerun. Selain itu, komponen tekanan liang udara yang sering diabaikan dalam perilaku tanah tak tepu semasa penyusupan air hujan juga disiasat menggunakan simulasi berangka dan permodelan fizikal kolum tanah satu dimensi (1D). Keputusan kajian menunjukkan bahawa pembangunan tekanan liang udara adalah dipengaruhi oleh jenis tanah, keamatan hujan dan kandungan air permulaan. Keputusan simulasi berangka dan eksperimen makmal menunjukkan bahawa sampel tanah dari tapak dengan keamatan hujan sebanyak 26751.6mm/hr dan kandungan air permulaan sebanyak 21% menghasilkan tekanan liang udara yang maksimum. Saiz zarah yang halus serta intensiti hujan dan kandungan air permulaan yang tinggi akan menyebabkan penyusupan air hujan tidak dapat menggantikan liang udara dengan lancar maka mengakibatkan tekanan liang udara meningkat.

DEVELOPMENT OF EVALUATION SYSTEM FOR GROUNDWATER LEVEL IN RELATION TO SLOPE STABILITY FORECASTING

ABSTRACT

The aim of this study focused on developing a new evaluation system of groundwater level for slope stability forecasting by conducting a case study at a cut slope in Precinct 9, Putrajaya, Malaysia. This system involved the development of subsurface conceptual model, development of groundwater table fluctuation model, stability assessment and investigation of unsaturated soil behaviour which incorporates the response of pore air pressure. Subsurface characterization of the study area was carried out by using the integration of borehole drilling, electrical resistivity survey and seismic refraction survey. Three dimensional (3D) models of stratigraphy, electrical resistivity and seismic velocity were proven to be effective in identifying the potential failure zone that coincides with the past slope failure zone. The potential failure zone that consist of silt soil was identified to have high water content with electrical resistivity ranges from 10Ωm to 300Ωm and intermediate P-waves velocity (v_p) of 500m/s to 1000m/s. Subsequently, the multi tank model and numerical analysis was developed to determine the groundwater table fluctuations and pore water pressure distributions of the slope. The multi tank model was able to produce a root mean square error (RMSE) of 0.156 and 0.169 for the calibration model using year 2011 data and prediction model using year 2012 data respectively. The factor of safety (FOS) of the slope throughout the year 2012 varies according to the fluctuations of groundwater table analyzed by using both limit equilibrium method (LEM) and finite element method (FEM). Furthermore, the FOS for the